Cyclic behaviour of timber-steel hybrid shear walls

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ABSTRACT: Timber-steel hybrid structures provide a viable solution to strengthen lateral load resisting systems in multi-storey timber residential buildings. This paper investigated cyclic behaviour of one type of timber-steel hybrid shear walls consisting of steel moment resisting frames and plywood infill walls. A detailed finite element model was developed to model the hybrid wall behavior under cyclic loading. The hysteretic parameters of critical connection elements were calibrated by experimental testing results. A parametric study was further conducted to investigate the effect of nail size and plywood thickness on the hybrid wall behavior. Overall, the hybridization of the steel moment frame and the plywood infill walls can provide significantly better performance compared with conventional plywood shear walls. And a combination of ϕ3.15x75mm nails with 17mm thick plywood in the infill wall seems to provide the optimal hybrid wall performance.

1 INTRODUCTION

Due to limited strength and stiffness of sawn timber, conventional light-timber frame (LTF) construction is uncommon to build multi-storey residential buildings in seismic regions such as New Zealand. Currently NZS3604:2011 for timber-framed buildings only allows to build LTF buildings up to a maximum of 2 or 3 storeys. In recent years, research has shown that timber-steel hybrid structures are able to provide high lateral capacity and have the potential to overcome the height restrictions of conventional LTF construction. Dickof et al (2012) introduced a timber-steel hybrid system consisting of steel frames and infill cross laminated timber (CLT) panels. He et al (2014) proposed a timber-steel hybrid system consisting of steel moment frames and oriented strand board (OSB) infill walls. Experimental investigations and numerical studies on these systems have been conducted to better understand the load sharing mechanism, critical design parameters and seismic performance (Li et al. 2014, 2015, and 2017).

The paper presents a numerical study on the cyclic behaviour of one type of timber-steel hybrid shear wall system consisting of steel moment frames and plywood infill walls, as shown in Figure 1. Two critical connections exist in the hybrid system: timber-sheathing connections and timber-steel connections. The timber-sheathing connections are comprised of plywood and timber framing members connected by nail fasteners. These connections provide ductility and energy dissipation for the infill wall via nail yield bending and wood embedment deformation. The timber-steel connections are comprised of timber framing members joined to steel framing members via bolts that can facilitate shear transfer from the steel frame to the infill wall. This study numerically investigates the effect of nail fasteners and plywood sheathing on the hybrid wall performance. Different nail sizes and plywood thicknesses are considered in the finite element (FE) hybrid wall modelling. In addition, experimental testing was conducted to evaluate the critical connection properties and calibrate the input parameters of the connection elements in the FE models. Critical shear wall properties such as strength, stiffness, ductility and energy dissipation are evaluated and compared between various wall configurations according to the FE modelling results.

2 HYBRID WALL MODELLING

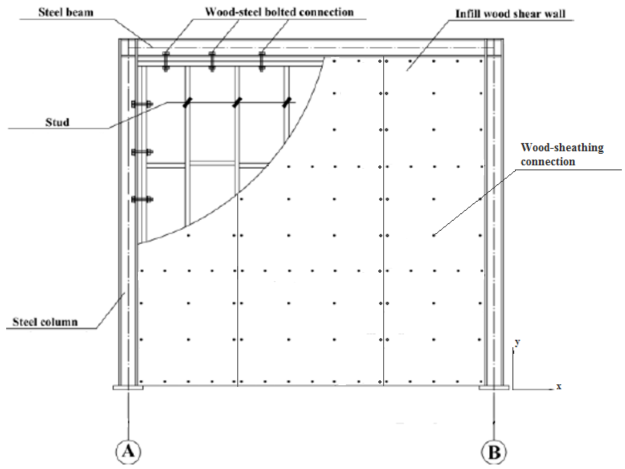

Figure 1: Configuration of a typical timber-steel hybrid shear wall

A detailed FE model of a timber-steel hybrid shear wall structure was developed in a software package called ABAQUS. The model is comprised of three types of elements: beam elements for timber and steel framing members, panel elements for plywood sheathing and spring elements for the timber-sheathing connections and timber-steel interface connections.

2.1 Framing and sheathing elements

Material properties of the steel beam elements (ABAQUS element B21) were defined as elastic-perfectly plastic. Beam-column joints were modelled as rigid connections. Column supports were modelled as rotational linear spring elements with a rotational spring stiffness of 2.015e7 kNm/rad based on previous research conducted by Dong (2017).

Plywood shear walls were modelled using existing plate elements (CPS4R) in ABAQUS. Material properties were taken as elastic. The (in-plane) average elastic modulus for plywood was taken both directions (parallel and perpendicular to face grain).

Timber framing members material properties was taken as elastic. Timber framing supports were modelled as rotational linear springs with a spring stiffness of 10000 kNm/rad. This allowed compression forces in the plywood to be resisted in shear by the supports, and later recorded to determine the force contribution in the plywood shear wall.

2.2 Connection elements

For the critical connections in the system, user defined nonlinear spring elements were used in the model. Their hysteric behavior was calibrated by experimental testing on a group of timber-steel and timber-sheathing connections. Non-critical connections such as the connections between timber framing members were simply assumed as pinned.

2.2.1 Experimental Testing of Connections

Following the ISO16670:2003 test standard monotonic and cyclic tests were conducted on a total of 240 nailed timber-plywood connections and 30 bolted timber-steel connections. The timber specimens were all made of Radiata Pine sourced from NZ. Plywood sheathing was Grade F8 manufactured to AS/NZS2269:2012. Timber studs were Stress Grade 8 (SG8) and manufactured to AS/NZS1748:2011. In the nailed timber-sheathing connections tests, three nail sizes (ϕ2.8x50mm, ϕ3.15x75mm, and ϕ3.55x90mm) and three plywood thickness (12mm, 17mm, and 25mm) were tested. Two loading orientations for timber-sheathing connections were considered – parallel to the timber and the plywood face grain and perpendicular to the timber grain and the plywood face grain. For the bolted timber-steel connections, the timber components were loaded parallel to the grain. Grade 300 M12 bolts were used. Figures 2 shows the test setups and typical load-slip hysteretic curves for the nailed connections and the bolted connections.

Figure 2 Test setup of nailed connections (left) and bolted connections (right) and typical load-slip hysteretic curves

2.2.2 Modelling of Connections

The nonlinear behavior of the hybrid shear walls is mainly governed by the critical connections and the steel MRF yielding under high loads. Therefore, it is important to incorporate robust connection elements for the hybrid wall model. As shown in Figure 4, Q-pinch hysteretic algorithm, proposed by Folz, et al (2001), was used to model the hysteretic behavior of the critical connections. In timber shear walls under lateral loads, nail fasteners tend to deform along different directions, and will not be restricted to only horizontal or vertical movement. Therefore, the oriented spring pairs proposed by Judd (2005) were also used to model the coupling behavior of the nailed connections along the original motion direction and the perpendicular to the original direction.

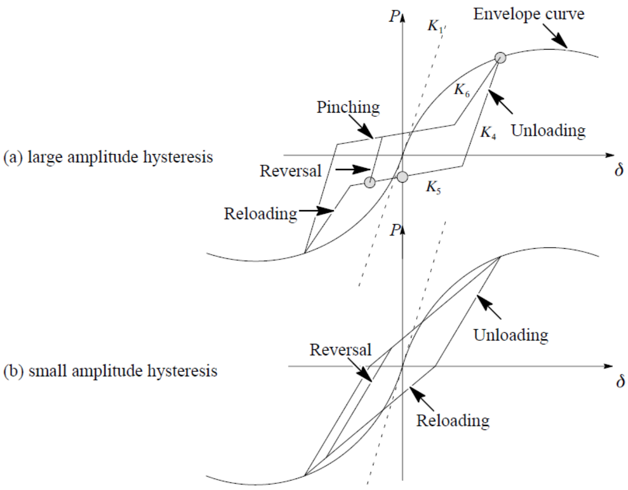

Figure 3: Q-Pinch model for connection hysteresis (Folz et al 2001)

For the bolted timber-steel interface connections, Li et al [6] suggested that these connections should be strong enough and avoid any premature failure before the failure of the infill wall. For these connections, the bolt fasteners are restrained by the flanges of steel members and the timber framing members under lateral loading. Therefore, it was assumed that these connections only deform in lateral and axial directions. Non-oriented (uncoupled) spring pairs were adopted to represent the connection behavior under shear loading and axial loading. The Q-pinch algorithm was used to model the connection behavior under shear loads. Elastic springs were used to model the connection behavior under axial loads.

In this study, the data obtained in experimental tests were used to calibrate the connection parameters. The average parameter values between the perpendicular and parallel to grain loading orientations were taken to represent the nails in the hybrid system. Table 1 lists the calibrated Q-pinch parameters for the nailed connections and the bolted connections under shear loads.

Table 1: Critical connections tested on and their calibrated parameters

Nail size	**Plywood thickness**	***Initial stiffness,*** k_1, **N/mm**	***Plastic stiffness,*** k_2, **N/mm**	***Degradation stiffness*** k_3, **N/mm**	***Unloading stiffness,*** k_4, **N/mm**	***Yield Force*** F_0, **N**	***Pinching Force*** F_1, **N**	Δ_y, **mm**	Δ_{ult}, **mm**	Δ_{fail}, **mm**	**Reloading degradation factor,** α	**Stiffness degradation factor,** β
ϕ2.8x50	12mm	846	25	38.5	920	782.5	175	1.1	9.9	16	0	1.1
ϕ 3.15x75	12mm	625	20	20	675	1120	250	2.0	7.3	21	0	1.05
ϕ 3.55x90	12mm	1243	39	33	1950	1070	320	1.1	10	20	0	1.1
ϕ2.8x50	17mm	850	35	60	1050	750	150	1.1	8.2	14	0	1.1
ϕ 3.15x75	17mm	1094	25	31.5	1450	1025	220	1.6	18.3	24	0	1.1
ϕ 3.55x90	17mm	970	27	35	1000	1090	305	1.1	12.6	25	0	1.1
ϕ 3.15x75	25mm	1131	34	35	1231	935	310	1.1	8.2	15	0.35	1.1
ϕ 3.55x90	25mm	1303	53	50	1903	1175	280	1.1	10	17	0.2	1.1
M12 Bolt	-	7200	7400	100000	7400	16500	4200	2.5	28	30	0.7	1.1

2.3 Validation of Hybrid Wall Models

The FE wall model was validated by experimental results of a hybrid shear wall consisting of a steel moment frame and an OSB infill wall. Detailed information about the experimental testing was reported by Dong (2017). The model input parameters for the critical connections were also calibrated by the experimental testing of the nailed timber-OSB connections and the bolted timber-steel interface connections. Figure 5 shows the tested wall configuration, the FE wall model, and the model predicted load-drift hysteresis compared with the results. It can be seen that the model prediction agreed well with the test results.

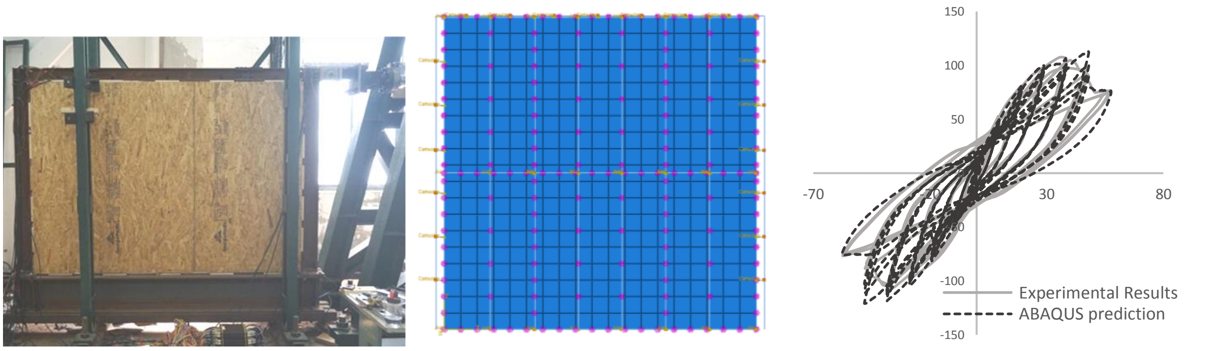

Figure 4: Hybrid wall configuration for model calibration (left). Detailed FE model of hybrid wall experiment (center). Hybrid wall model prediction vs. experimental results (right)

3 PARAMETRIC ANALYSIS

3.1 Wall configuration

Using the validated FE hybrid wall model, a parametric study was carried about on a 3.6m x 2.4m hybrid wall consisting of a steel moment frame and infill plywood shear walls. As shown in Figure 5, the wall configuration was chosen for NZ applications. The types of steel beams and columns, timber members, plywood sheathing, and metal fasteners with the corresponding properties are given in Table 2. The numerical model was subjected to a cyclic loading protocol based on ISO16670:2003. In the parametric study, the configuration of the steel frame was fixed while different combinations of nail fasteners and plywood thickness were considered.

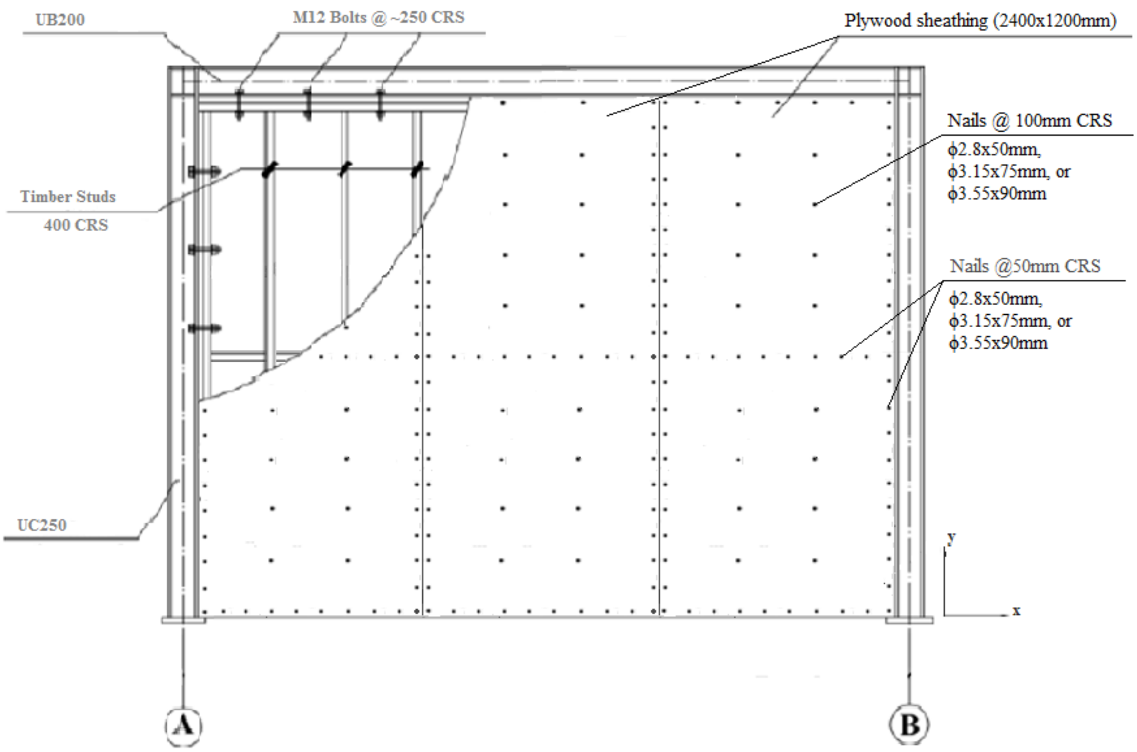

Figure 5: Structural configuration of timber-steel hybrid shear wall

Table 2: Structural properties adopted in the hybrid system

Component	*Size*	ρ	*E (*MPa*)*	*v*	*G (*MPa*)*	σ_y (MPa)	σ_p (MPa)	ε_p
Steel beam	200UB	7850	210E3	0.3	-	300	301	0.001
Steel column	250UC	7850	210E3	0.3	-	300	301	0.001
Plywood	12, 17, 25mm	650	Ex = Ey = 9100	0.12	455	-	-	-
Timber frame	90x45mm	450	8000	0.3	-	-	-	-
Nails	ϕ2.8x50, ϕ3.15x75, ϕ3.55x90	-	-	-	-	-	-	-

3.2 Results

Table 3 shows the results of the parametric study. Figure 6 shows typical load-drift hysteretic curves of the bare steel frame, the plywood infill wall if working on its own, as well as the hybrid wall system. The wall parameters such as strength, stiffness and ductility ratio μ were evaluated as per ASTM E2126 [13].

Table 3: Summary of parametric study results

Wall #	Nail size	Plywood thick-ness	P_{peak}, kN	$P_{infill, peak}$, kN	k_{hybrid}, kN/m	k_{infill}, kN/m	R	P_{yield}, kN	Δ_y, mm	Δ_{ult}, mm	μ	E_{diss} (kJ)
1	ϕ2.8 x 50	12mm	182	105	4.7	3.0	1.8	151	23.7	142	6.0	12.7
2	ϕ 3.15 x 75	12mm	204	126	4.3	2.7	1.6	171	29.1	195	6.7	28.2
3	ϕ 3.55 x 90	12mm	224	147	5.1	3.6	2.3	176	25.1	180	7.2	26.6
4	ϕ 2.8 x 50	17mm	180	144	5.2	3.6	2.2	146	20.7	102	4.9	12.3
5	ϕ 3.15 x 75	17mm	223	140	5.6	4.0	2.5	182	23.8	216	9.1	35.2
6	ϕ 3.55 x 90	17mm	222	144	5.4	3.8	2.3	182	24.8	180	7.3	28.7
7	ϕ 3.15 x 75	25mm	201	123	6.3	4.7	3.0	165	19.2	142	7.4	20.3
8	ϕ 3.55 x 90	25mm	242	168	6.6	5.1	3.4	192	21.2	160	7.6	24.8
Avg			210	137	5.4	3.8	2.4	171	23.4	165	7.0	23.6

Note: R is defined as k_{infill}/k_{bf}, and k_{infill} is the initial stiffness of plywood infill wall and k_{bf} is the initial stiffness of the bare steel frame; E_{diss} is the total energy dissipation of the shear wall.

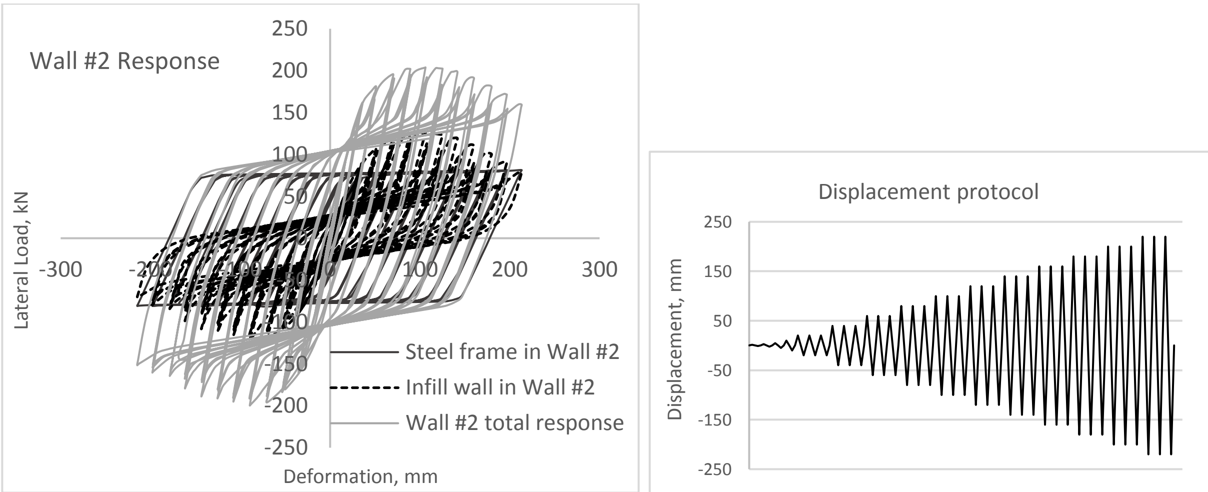

Figure 6: (Left): Typical hybrid shear wall response. Note contributions from steel frame and plywood infill wall. (Right): Cyclic loading protocol as per ISO16670:2003

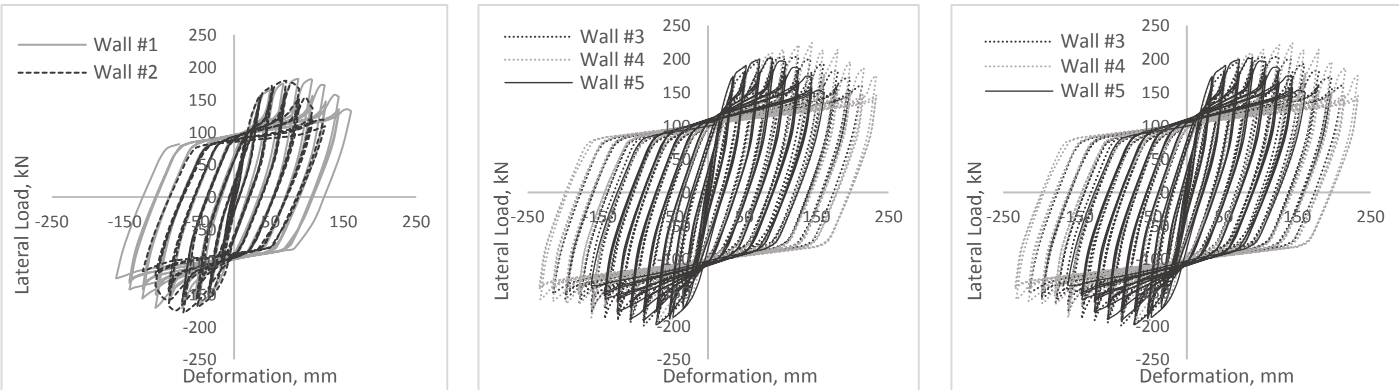

Figure 7: Hysteresis curves of Wall #1 to Wall #8

3.3 **Discussion**

The hybridization of the steel moment frame and infill plywood shear wall significantly increased the wall stiffness and strength compared with plywood shear walls acting independently. Depending on the type of infill wall configurations, the addition of steel moment frame increased the wall stiffness by 32% – 57% and the peak loads by 25% – 73%. It was also found the plywood infill wall carried the majority of the lateral load during initial stages of loading (between 64% – 77%) and dissipated the seismic energy through nailed connections. The ductility ratios of the hybrid walls ranged from 4.9 to 9.1, indicating good ductility of the system.

3.3.1 *Effect of plywood thickness on hybrid system*

Adoption of larger nails and thicker plywood tends to increase the load carrying capacity of the hybrid walls. However, this is not always the case. In the wall configurations using ϕ3.15x75mm nails where the peak load decreased when the plywood thickness increased from 17mm to 25mm. This is because the capacity of the hybrid system is affected by the timber-sheathing connection strength which is dependent upon a number of connection parameters such as nail size, plywood thickness, timber density and nail penetration depth as well. Due to the fact that the penetration length of the nail fastener decreased from 58 mm to 50 mm as plywood thickness increased from 17mm to 25mm, the connection strength drecreased leading to the reduction of the hybrid wall capacity.

The infill wall-to-bare frame stiffness ratio R of the hybrid system has a positive trend with increases in plywood thickness. In this study, R ratios increase between 9% – 56% as plywood thickness is incrementally increased, regardless of the nail size combination. This translates to 9.8% – 30.2% increases in the initial stiffness of the hybrid system. An R ratio greater than 1 will allow the infill walls will carry higher lateral loads than the bare steel frame during the intial stages of loading.

It was also found that the highest ductility factors were provided by the timber-sheathing connections using 17mm thick plywood in combination with larger nails (ϕ3.15x75mm and ϕ3.55x90mm). 17mm thick plywood with smaller nails (ϕ2.8x50mm) is not advised due to insufficent nail penetration length.

3.3.2 *Effect of Nail size*

The parametric study also showed that the nail size inrease (ϕ2.8x50mm, ϕ3.15x75mm, ϕ3.55x90mm) generally increased both the load carrying capacity by 10% – 24%. Increasing nail size also generally increases the ductility. However, in the timber-sheathing connection configurations using 12mm and 17mm plywood, Numerical models of the experimental nail connection data show that ϕ3.55x90mm nails used in combination with 12mm and 17mm ply have smaller ultimate displacements than ϕ3.15x75mm nails used with 12mm and 17mm ply. Results show that using timber-sheathing connections with ϕ3.15x75mm nails in combination with either 12mm or 17mm thick plywood provide the largest ductility factors. Larger nails are recommended to meet requirements for higher peak loads. ϕ3.15x75mm nails seem to provide the greatest ductility while providing comparable strengths to the larger ϕ3.55x90mm nails.

4 **CONCLUSION**

The hybrid walls consisting of steel moment frames and plywood infill walls had significantly high load carrying capacity and initial stiffness than conventional plywood shear walls, while maintaining good system ductility. In some cases, the load carry capacity and initial stiffness was almost twice of those of the plywood shear walls. This provides great benefits in terms of limiting non-structural damages under serviceability level earthquakes and increased load carrying capacity under major earthquakes.

Increased nail size and plywood thickness tend to increase the load carry capacity and stiffness of the hybrid system. However, proper nail size and plywood thickness should be checked to eliminate the non-ductile nailed connection behavior in the infill walls.

A combination of ϕ3.15x75mm nails with 17mm thick plywood in the infill wall provided the optimal hybrid wall performance in terms of strength, initial stiffness, ductility and energy dissipation.

The parametric study was limited to one type of steel moment frame with a given wall dimension. Further research is needed to consider the influence of the steel frame design on the overall hybrid system behavior.

5 ACKNOWLEDGEMENT

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